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Smart Grid Research in a Danish Perspective

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Smart Grid Research in a Danish Perspective

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9 March 2014

Center for Electric Power and Energy (CEE)
Department of Electrical Engineering

- CEE established 15 August 2012 as a merger of existing units:
  - Center for Electric Technology, DTU Electrical Engineering
  - Intelligent Energy Systems, Risø National Laboratory for Sustainable Energy
- Main competences
  - Electric Power Engineering
  - Automation and control
  - Information and Communication Technology
- A strong university centers within its field
  - Approx. 100 staff incl. approx. 30 PhD-students
  - Covers discipline oriented research as well as national lab type application-driven research and proof-of-concept
- Strategic partnerships

Selected National and International Collaboration Partners

- ***Academic partners:***

ETH Zürich (CH)
TU Delft – Delft University of Technology (NL)
Tsinghua University – 1911 (CN)
NORDIC FIVE TECH: DTU (DK), NTNU – Norwegian University of Science and Technology (NO), Aalto University School of Science and Technology (FI), CHALMERS (SE), KTH (SE)
Berkeley – University of California (US)
University of Strathclyde Glasgow (UK)
University of Delaware (US)
The Hong Kong Polytechnic University 香港理工大學 (HK)

- ***Commercial and industrial partners:***

ENERGINET.DK (DK)
DONG energy (DK)
SIEMENS – Siemens Wind Power (DK)
elia – Powering a world in progress (BE)
ØSTKRAFT – energi til gode oplevelser (DK)
nationalgrid (UK)
IBM (CH)
Vestas (DK)
Pacific Northwest National Laboratory (US)
Danfoss (DK)
seas nve (DK)
SIEMENS (DE)
VESTFROST SOLUTIONS (DK)
nkt cables (DK)
+ SME's

- ***International networks:***

SMARTGRIDS (EU)
EERA – European Energy Research Alliance (EU)
iea Energy Technology Network; ISGAN – international smart grid action network (Global)

Smart Grids in Denmark

- Smart Grid is a prerequisite for efficient integration of high share of renewable energy. Smart Grid makes an overall positive business case in DK (ref: Energinet.dk / Danish Energy Association)

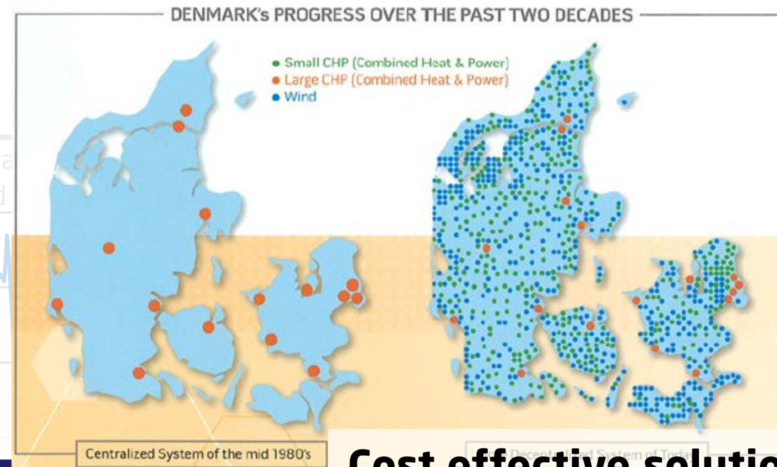
- Electricity expected to doubles to ~70% of the total energy system (ref: DK Climate Commission)

- Status in Denmark
  - Wind power generation is equal to 33% of demand (2013)
  - The EU country with the highest share of the export within energy technology (~12%)
  - Ambitious goals: 50% wind in 2020; No fusil fuels in 2050 (ref: DK Government)
  - National consensus: National smart energy partnership under establishing. National smart grid strategy to be launched.

Some Main Research Challenges (and The Danish Wind Power Case)

Balancing:

Changed Generation Landscape:

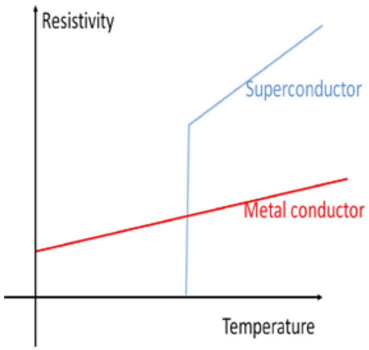


Stability and Reliability:

Cost effective solutions:

Superconducting Wind Turbine Generators

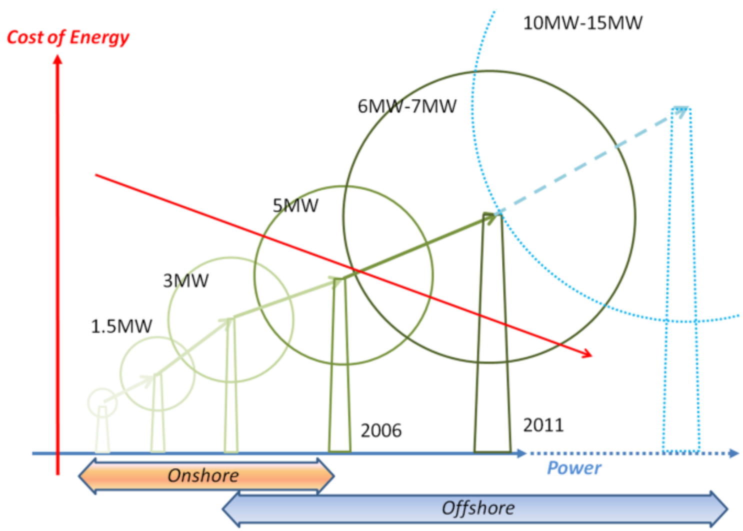
by Assoc. Prof. *Bogi Bech Jensen*, Electric Components group

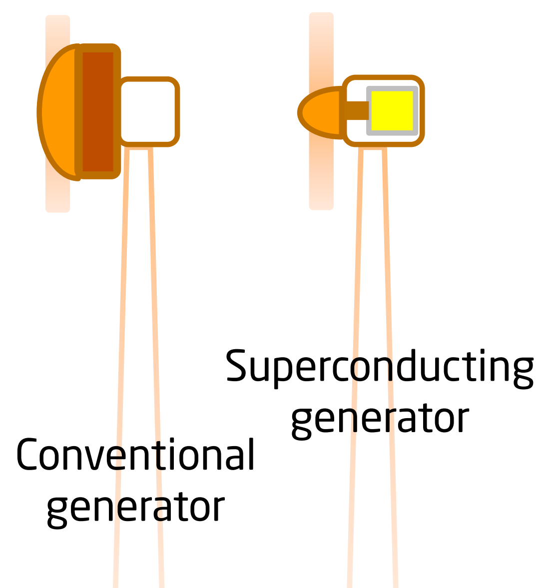


- Zero resistance
- Low operating T

$$P = \omega_m T$$

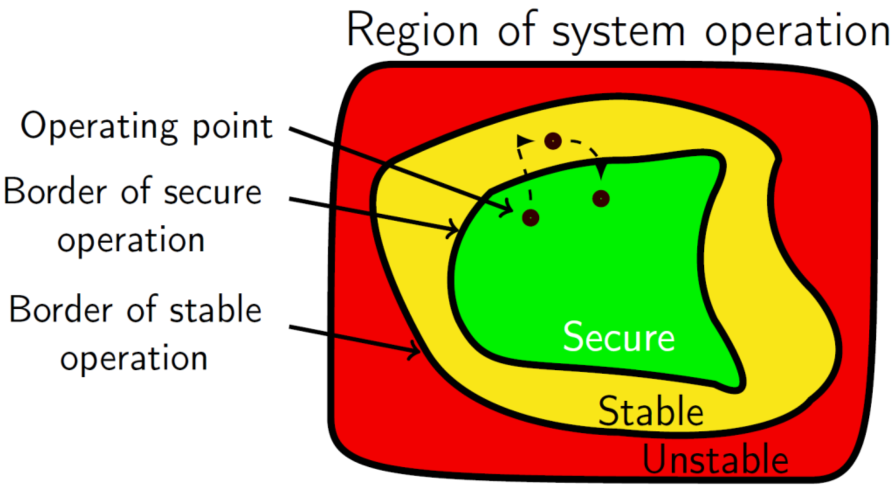
$$T = \sqrt{2} A \hat{B}_g V$$

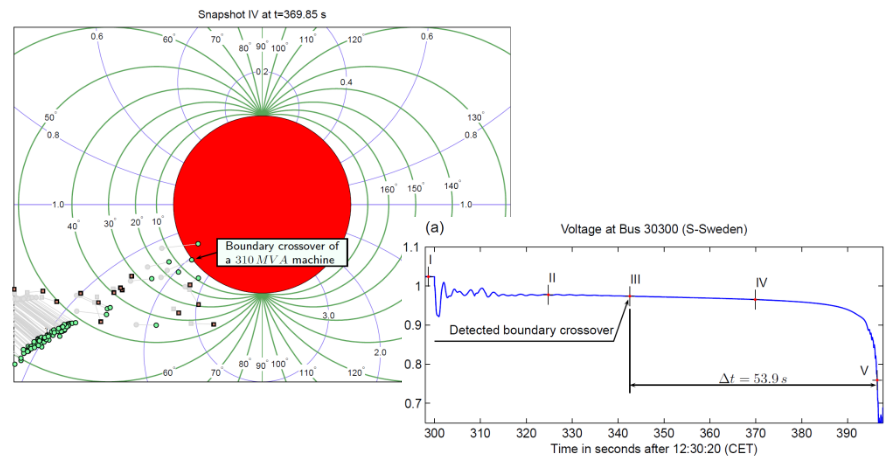




Refs: Patent application, 2012.
IEEE Transactions on Applied Superconductivity, June 2011.

Stability and security assessment in real time (ms-range)





Conventional approaches:

- Historically off-line analysis
- Assessment times of 5 – 15 minutes
- Insufficient for systems with high share of stochastic energy sources

Developed approach:

- Real-time monitoring of operating condition
- PMU's as enabling technology
- Analytical approach
- Assessment time (7917 nodes, 1325 gens, ≈2.5 ms)
- Early warning (2003 SW-DK blackout -> Δt ≈80 s)
- Remedial actions can easily be calculated (wide area control)

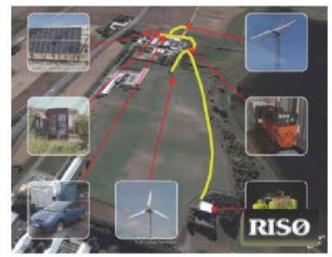
Refs: *International Journal on Power and Energy System*, 2012
Patent No. 111681113.6 – 2207, 2011
Patent No. EP11195960.7, 2011

PowerLabDK combines experimental facilities

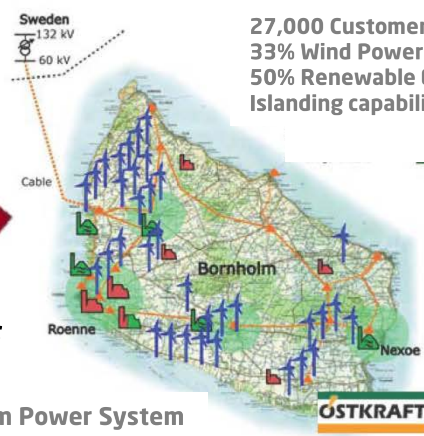
Flexible multi-purpose laboratories

Lyngby & Ballerup Campus

Large-scale test system



Risø Campus



27,000 Customers
33% Wind Power
50% Renewable Energy
Islanding capability

Full-scale Realistic Power System

Bornholm Power System

Stakeholders:

ABB, nkt cables, dansk energi, SIEMENS, DONG energy, VATTENFALL, ENERGINET/DK, Vestas, IBM

Supported by:

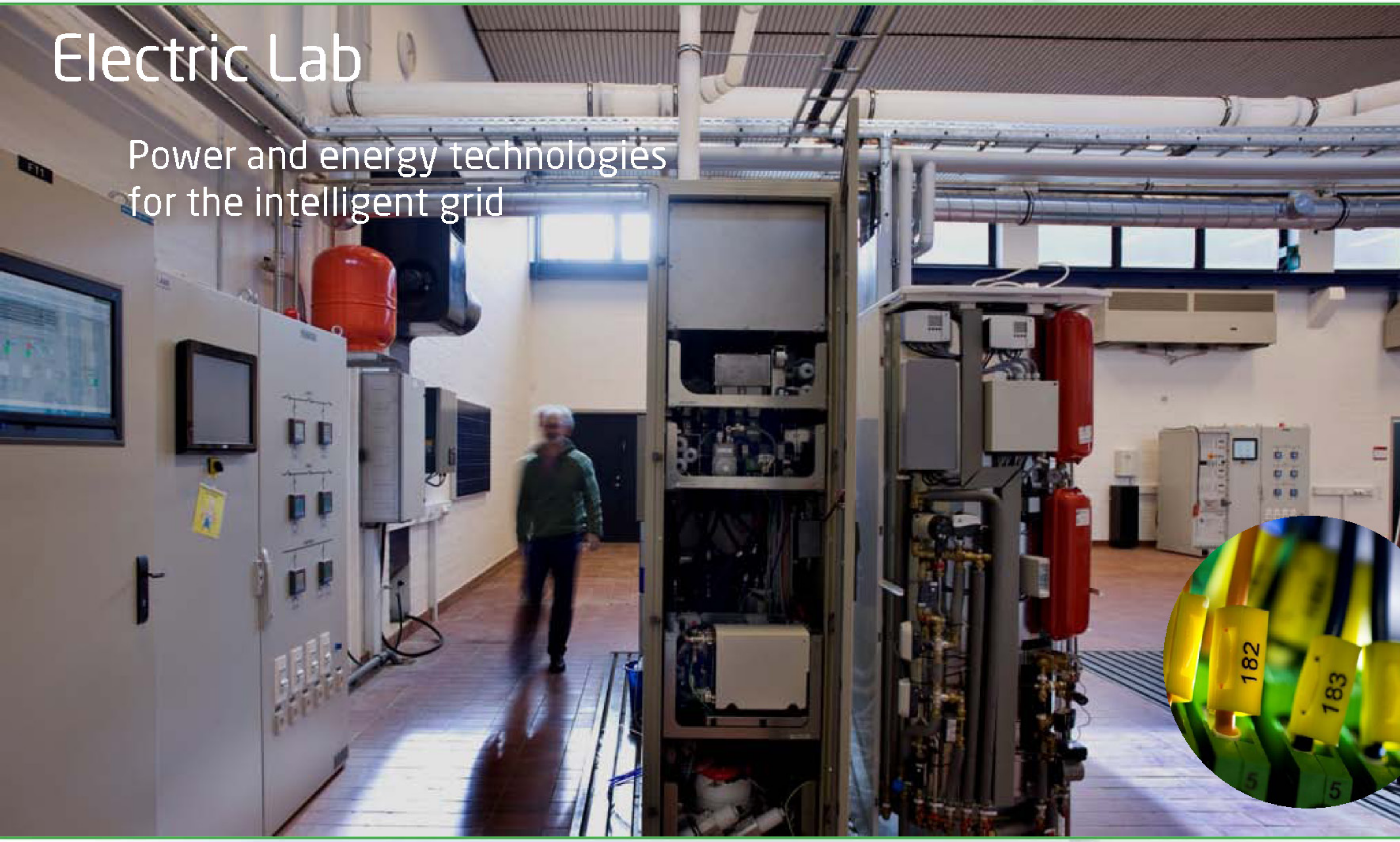
GREEN LABS DK, EUDP

Investment:
18 million Euro

PowerLabDK

Electric Lab

Power and energy technologies for the intelligent grid



www.powerlab.dk

DTU Technical University of Denmark

INGENIØRHØJSKOLEN KØBENHAVN - University College

ØSTKRAFT energi til gode oplevelser

PowerLabDK

Intelligent Control Lab

Power system simulation, control and supervision

www.powerlab.dk

DTU Technical University of Denmark

INGENIØR HØJSKOLEN KØBENHAVN - University College

ØSTKRAFT energi til gode oplevelser

PowerLabDK

High Voltage, High Power and Student Labs

Components in interaction with complex energy systems

www.powerlab.dk

DTU Technical University of Denmark

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ØSTKRAFT energi til gode oplevelser

PowerLabDK

SYSLAB and PowerFlexHouse

Intelligent distributed energy system in practice

www.powerlab.dk

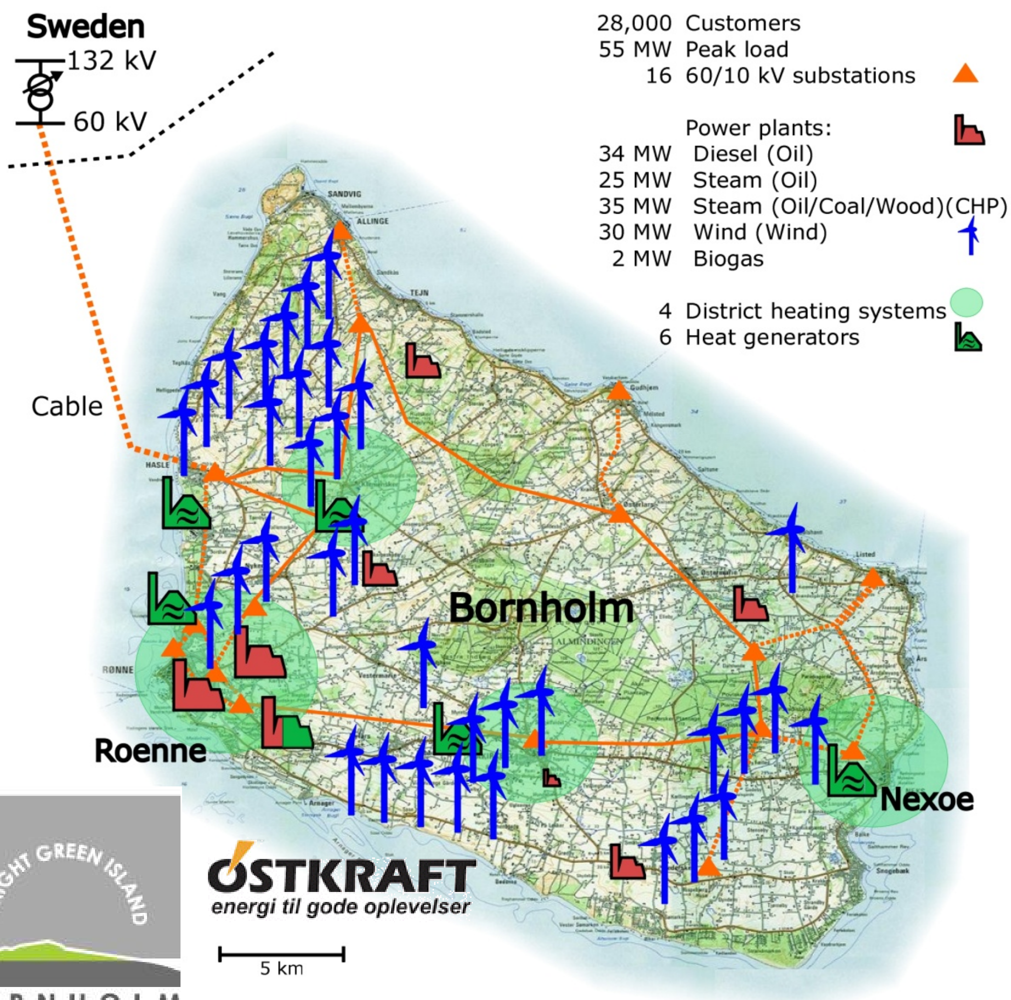
DTU Technical University of Denmark

INGENIØR HØJSKOLEN KØBENHAVN - University College

ØSTKRAFT energi til gode oplevelser

Bornholm Full-Scale Laboratory (1% of DK)

33% Wind Power Penetration; 28,000 Customers



Local Energy Strategy
Political & public drive

BORNHOLM.DK
BRIGHT GREEN ISLAND

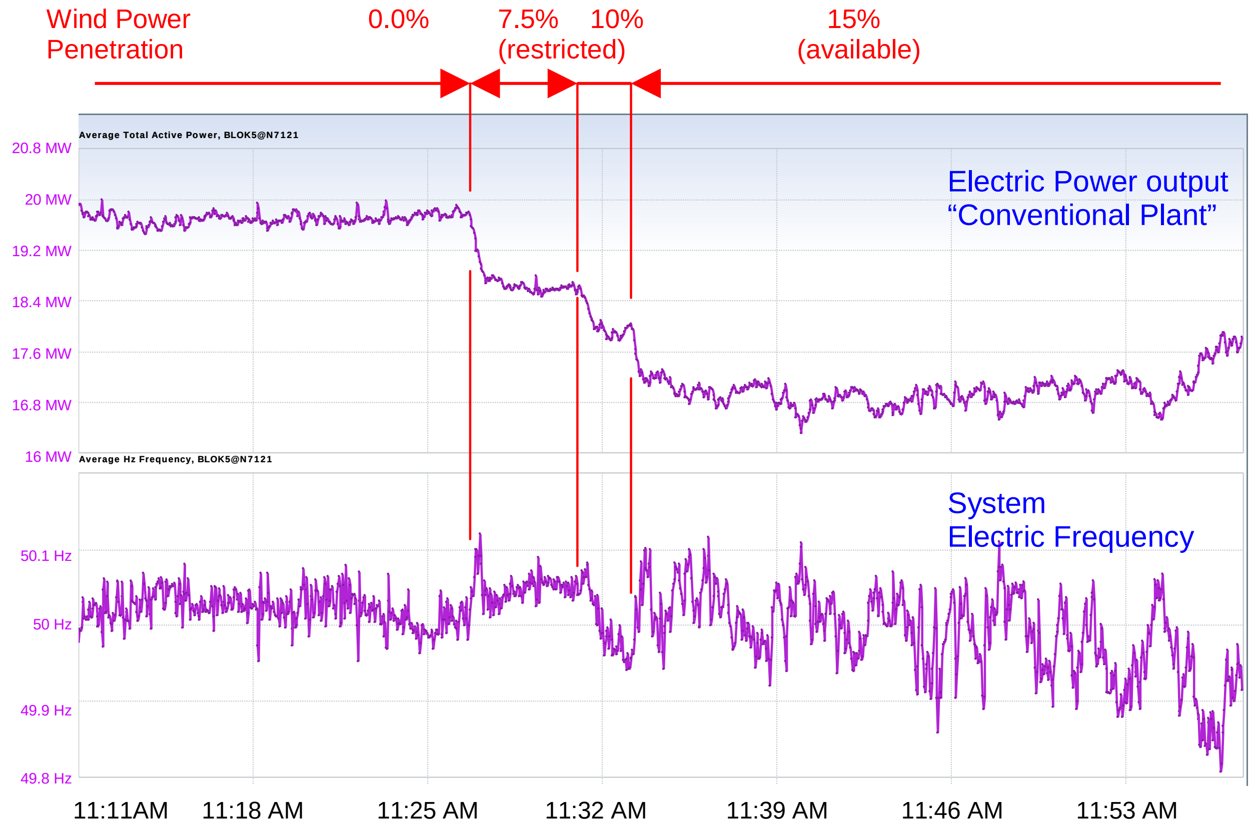
Energy resources:

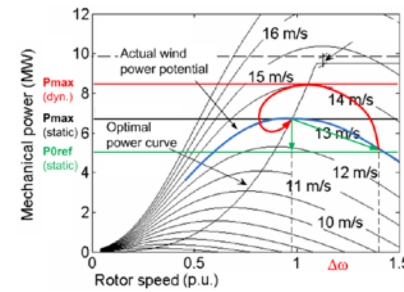
- *Wind power*
- *Biogas plant*
- *Combined heat and power*
- *District heating*
- *Solar power*
- *eMobility*

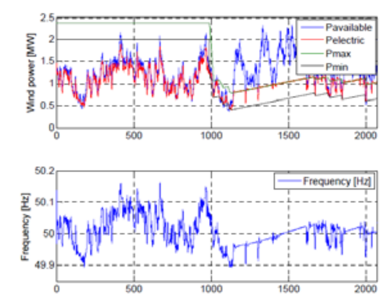
Features:

- *Nord Pool market (DK2)*
- *Islanding capability*

Bornholm Islanding Experiment



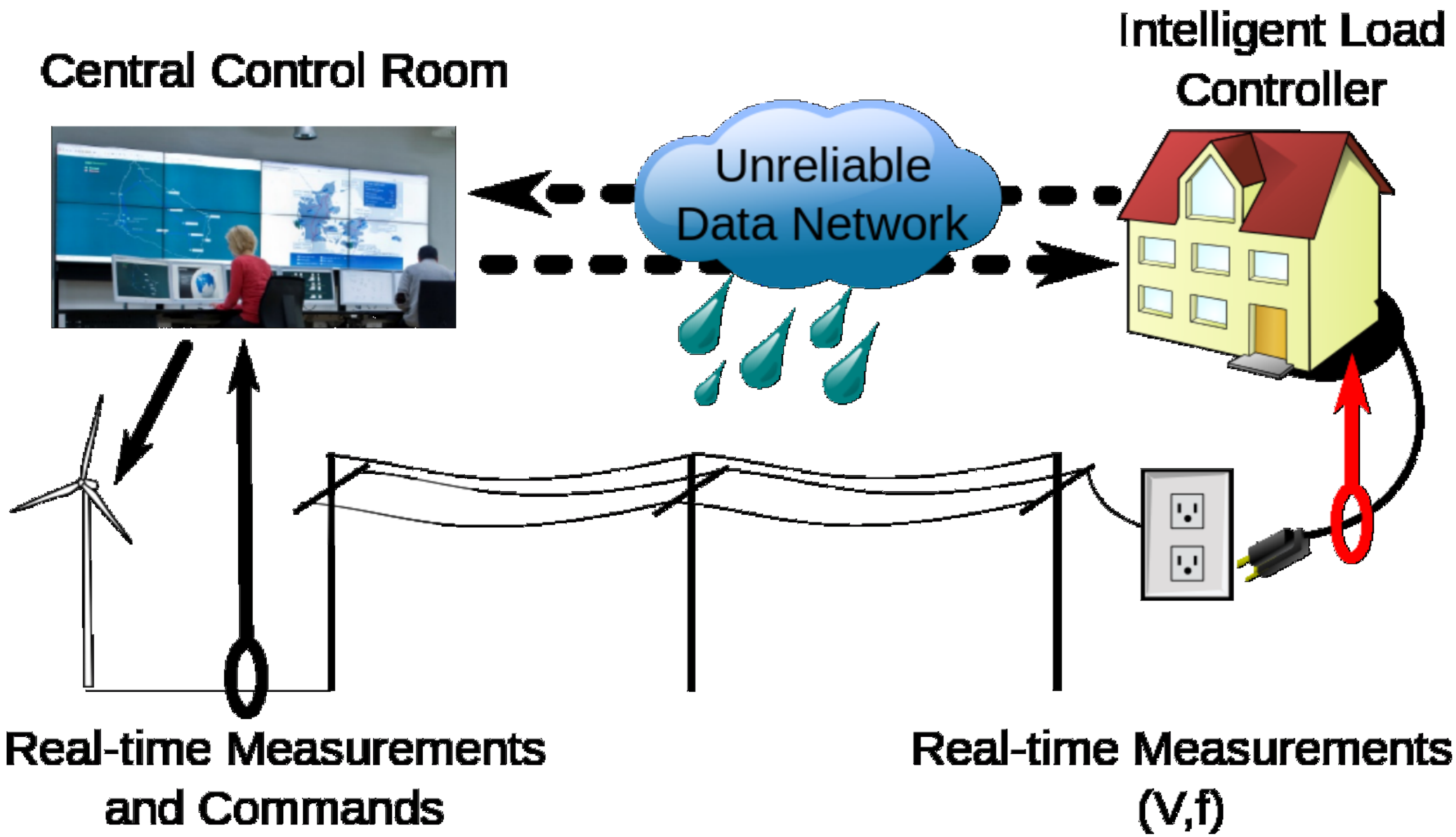




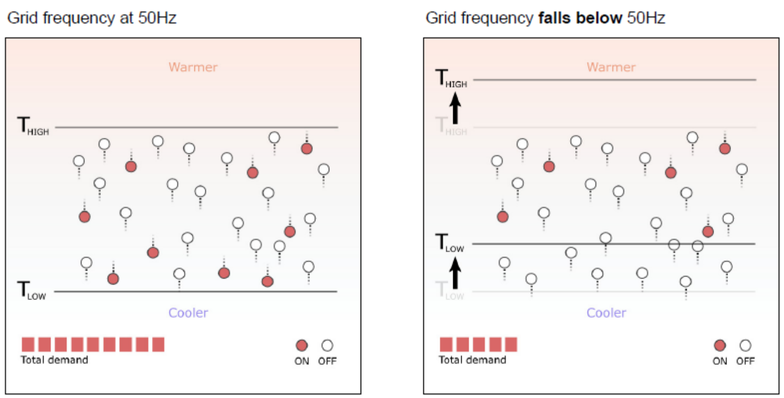
Vestas
No.1 in Modern Energy

Refs: *9th International Workshop on Large-Scale Integration of Wind Power*, 2011
Patent No. US20120161444, 2011

Autonomous V- and f-services from demand

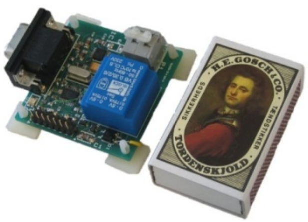


System Reserves Provided by Frequency Responsive Electricity Demand



$$T_{high} = T_{high}^{normal} - kf(f - f_0)$$

$$T_{low} = T_{low}^{normal} - kf(f - f_0)$$



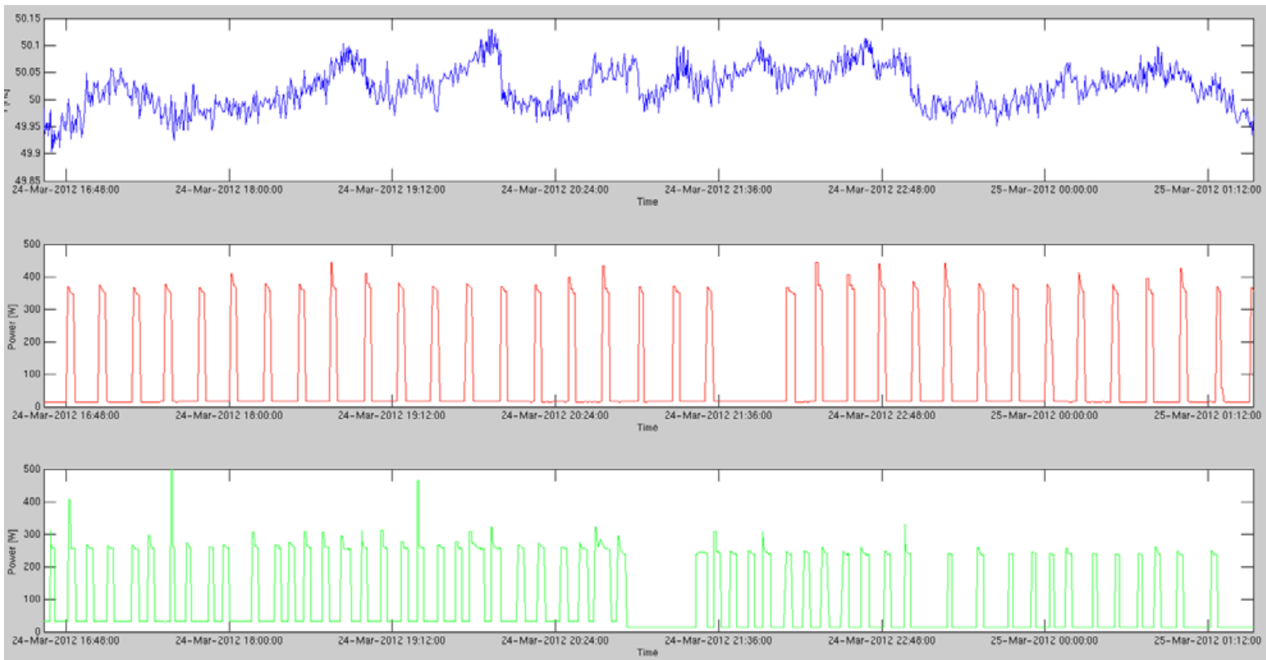
Field test at Bornholm

Field test w. 200 residential, commercial and industrial demand units

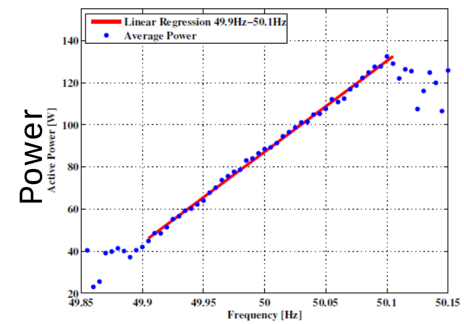
Refs: *IEEE Transactions on Power Systems*, August 2011.
IET Generation Transmission and Distribution, August 2009.

System Reserves Provided by Frequency Responsive Electricity Demand
Field measurements

Operation of single bottle cooler



Delivery of normal reserve (49.9-50.1 Hz)



Delivery of disturbance reserve (<49.9 Hz)

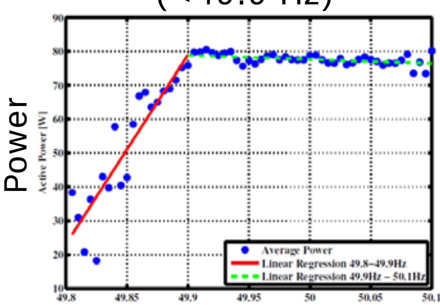
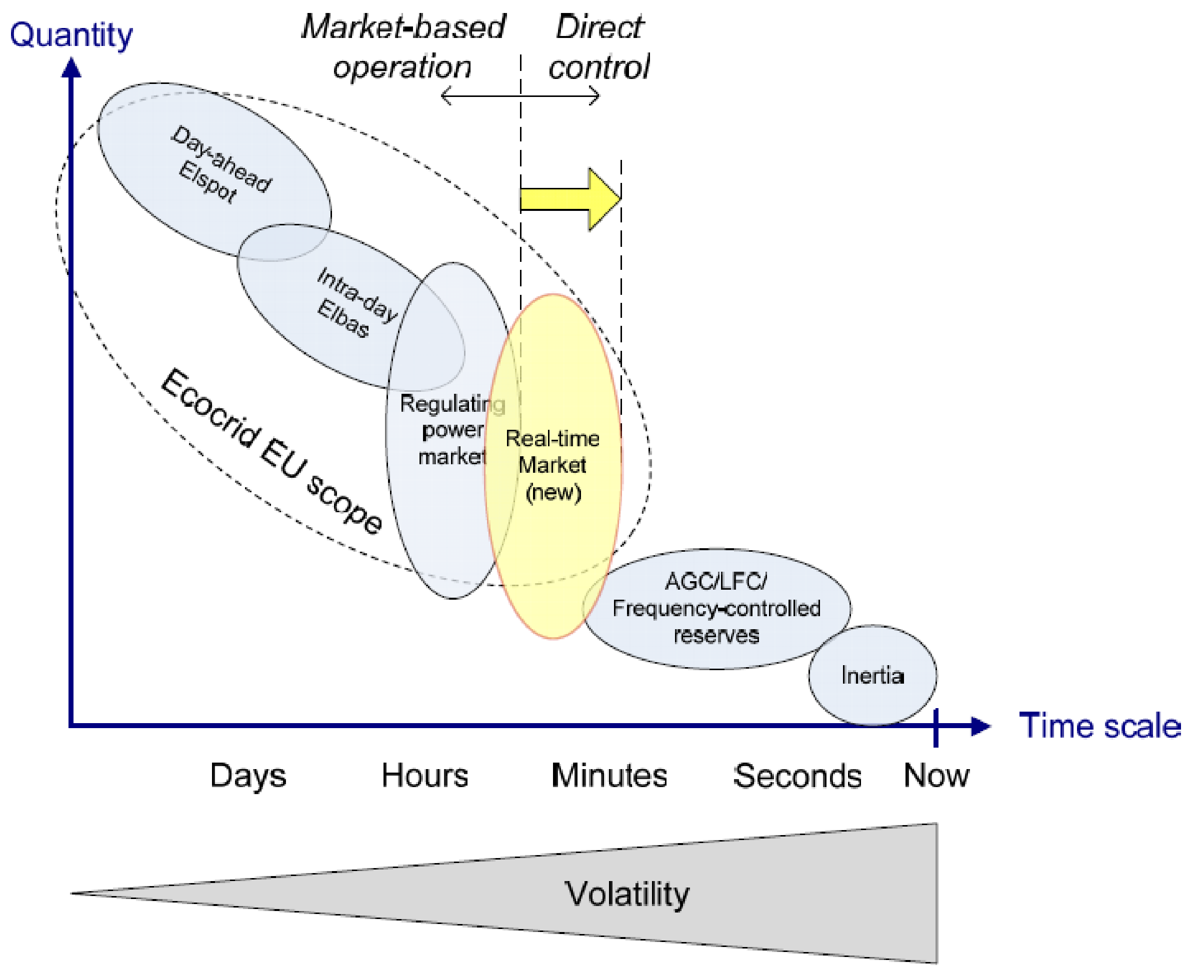


Figure 9. Frequen... ng as a disturbance reserve, shown with ... regression in regions above and below 49.90 Hz.

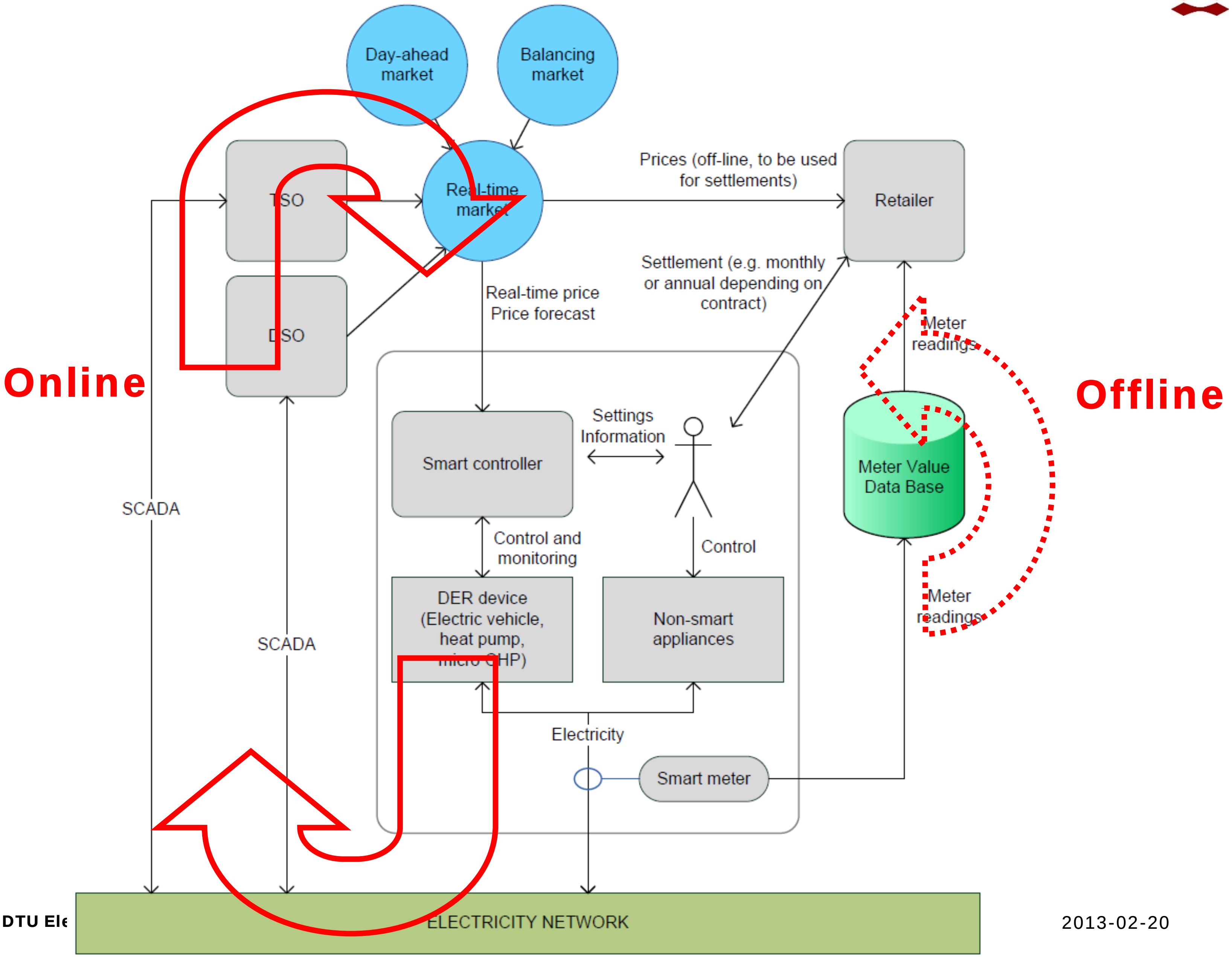
- Demand can with maintained energy service deliver reserves which today are delivered by large power plants
- Simple pay back time = 1-2½ year w/ 1 kW unit
- Easy implementation supporting commercialization

Extention of the Electricity Market Solutions
Smaller Participants and Shorter Time Constants



Why Do We Need a New Real-Time Market?

1. More wind -> less predictability
   - Calls for market clearing near the time of delivery
2. More wind -> more fluctuation
   - Calls for markets with higher time resolution
3. Less dispatchable generation
   - Calls for demand-side participation
4. Increased use of electricity for heat and transportation
   - Calls for local congestion management


Day-ahead market
Balancing market
TSO
Real-time market
Prices (off-line, to be used for settlements)
Retailer
DSO
Settlement (e.g. monthly or annual depending on contract)
Real-time price
Price forecast
Meter readings
Online
Offline
Settings Information
Smart controller
Meter Value Data Base
SCADA
Control and monitoring
Control
DER device (Electric vehicle, heat pump, micro CHP)
Non-smart appliances
SCADA
Meter readings
Electricity
Smart meter
ELECTRICITY NETWORK

Comparison with the Nordic Regulating Power Market

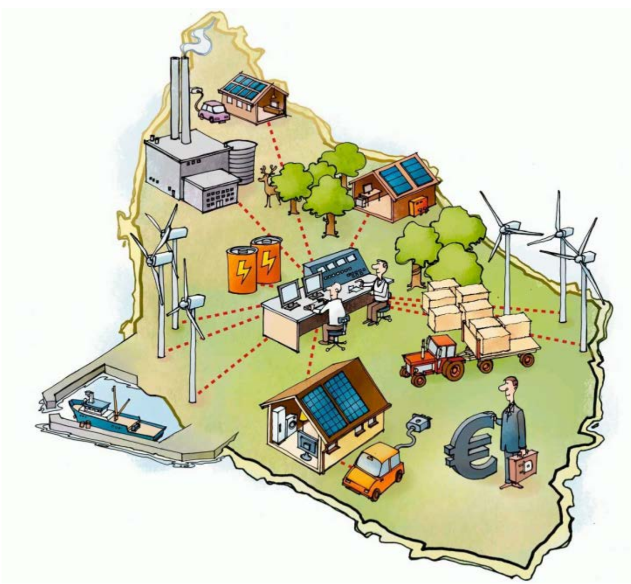
- **Regulating power market**
- Market resolution: 1 hour
- Submit bids no later than 45 mins before each hour
- Full response in less than 15 minutes
- Sustain response for up to 1 hour
- Works well with hydro power, thermal power plants and gas engines

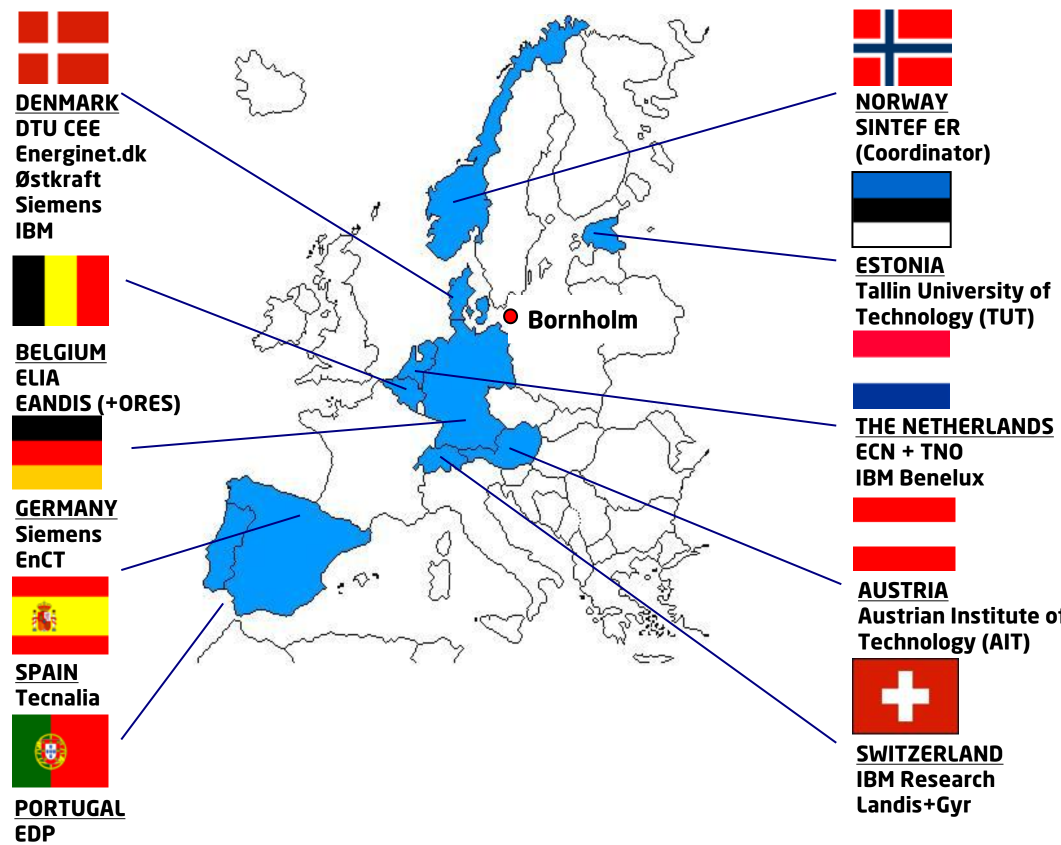
- **Real-time market**
- Market resolution: 5 minutes
- No bids
- Price takes effect immediately
- No promises made
- Works well with loads, wind and micro-generation

EcoGrid EU

Large-scale demonstration of the future intelligent distribution system

- Integrated research and large-scale demonstration of Smart Grids
- ~2,000 active customers
- EU fast-track to Smart Grids
- 2011-14
- 21 million Euro





Awarded *World's Best Sustainable IT-project 2012* by Arnold Schwarzenegger et. al

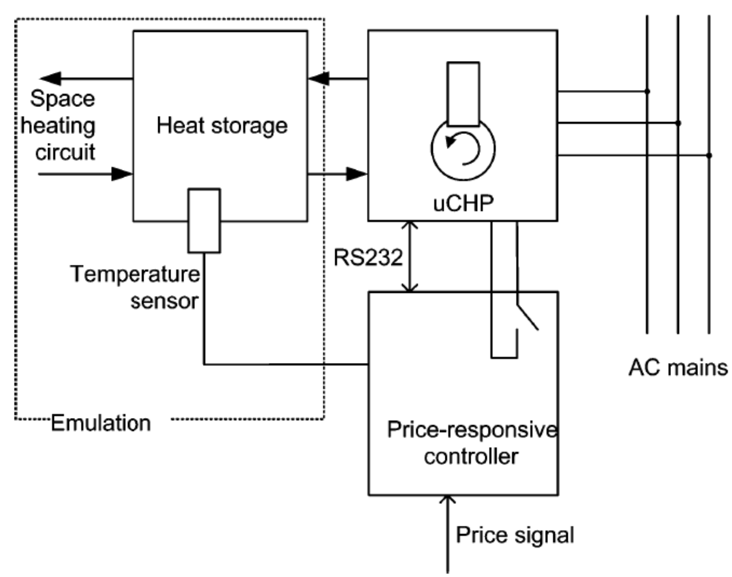
Micro-CHP Unit in PowerLabDK Laboratory at DTU
Gas-engine based Senertec DACHS

TABLE V
MICRO-CHP THERMAL PARAMETERS

Building heat demand	6 kW ± 50%
Storage tank capacity	750 liter
Min. heat storage av. temperature	50 ºC
Max. heat storage av. temperature	80 ºC

TABLE V
MICRO-CHP CHARACTERISTICS

Electric power	5.5 kW
Heating power	12.5 kW
Start-up delay	90 seconds
Shut-down time	Immediately
Minimum on-time	30 minutes



Relative Price

Example from the Nordic System 25 September 2009

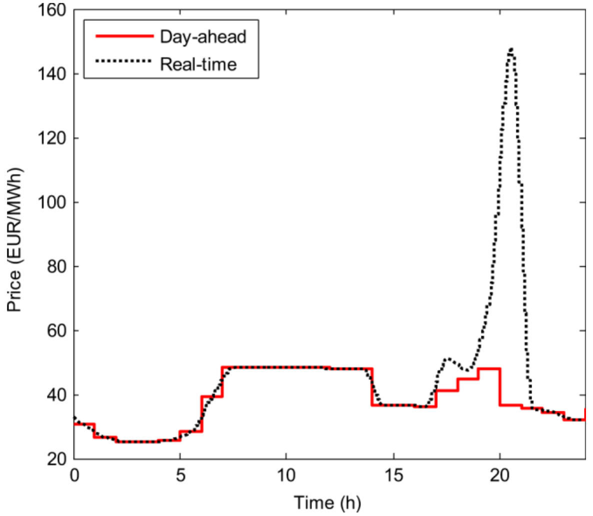
Relative price:

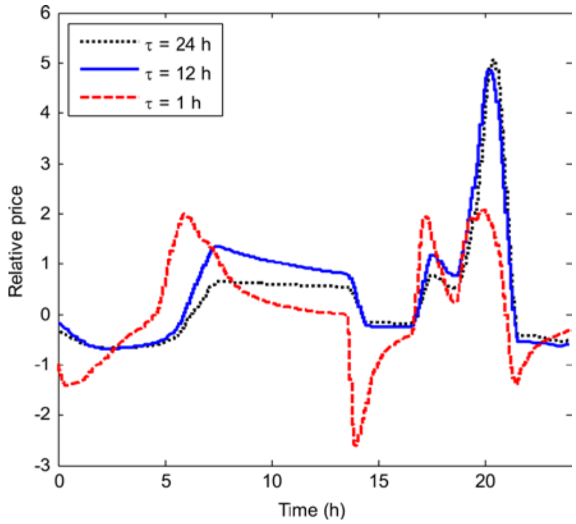
$$P_{rel} \equiv \frac{P - P_{avg}}{P_{dev}}$$

$$P_{avg,i} = P_{avg,i-1} + \frac{\Delta t}{\Delta t + \tau} \cdot \left(P - P_{avg,i-1}\right)$$

$$P_{\text{var},i} = P_{\text{var},i-1} + \frac{\Delta t}{\Delta t + \tau} \cdot \left(\left(P - P_{avg,i}\right)^2 - P_{\text{var},i-1}\right)$$

$$P_{dev,i} = \sqrt{P_{\text{var},i}}$$

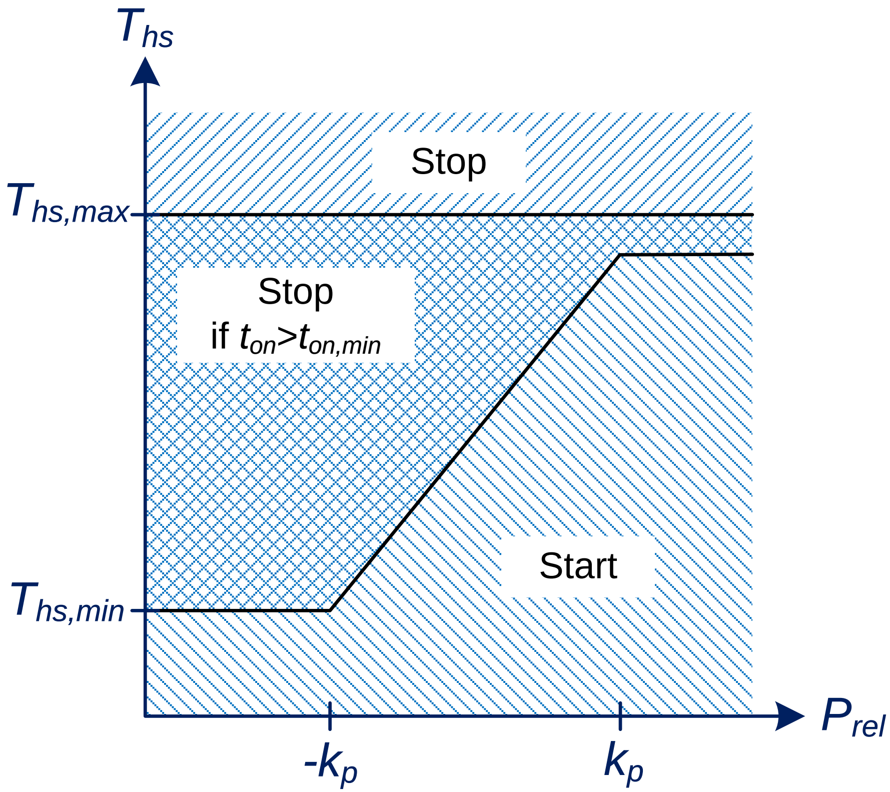




Very simple implementation.

Micro-CHP Control

Decision diagram:



T_{hs}: Heat storage average temperature (state-of-charge)

t_{on}: Minimum operating time per start

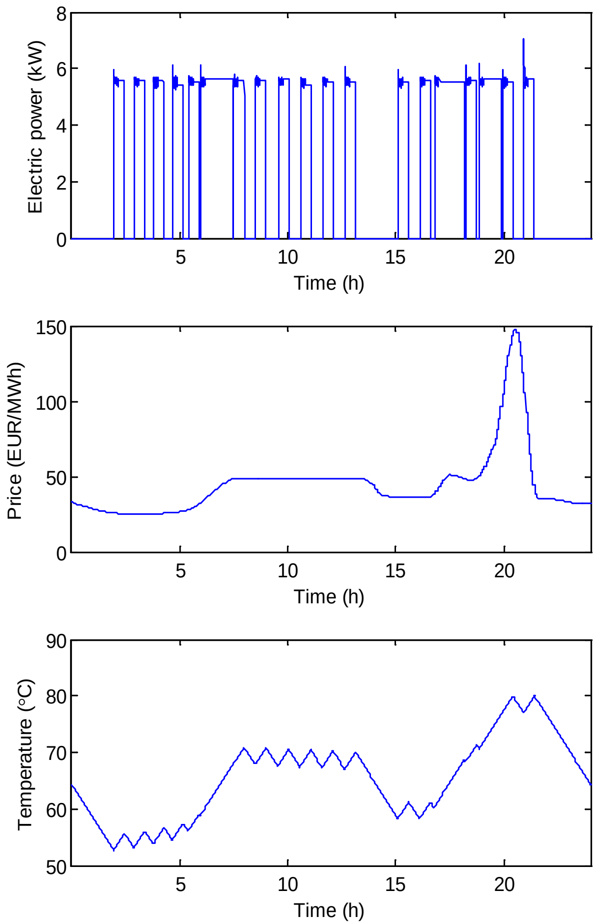
k_p: The relative price at which the controller will fully charge the heat storage

TABLE V
MICRO-CHP CONTROLLER

Price constant, k_p	1
Relative price time constant, τ	12 h

Operation with Prices of 25 September 2009

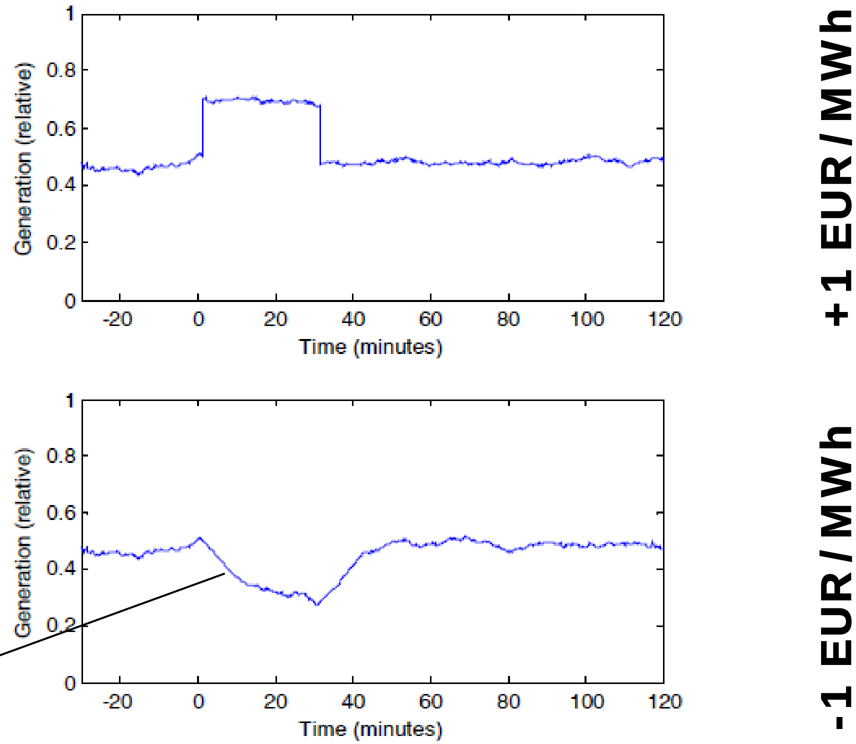
Measurement in Laboratory



Increased income is **7.3 %** without loss of comfort.

Response @ 1 EUR/MWh Price Step

Simulation of 1,000 units



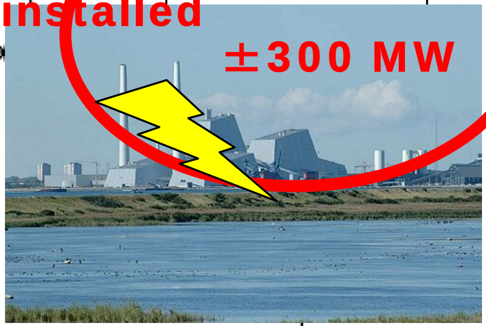
Minimum on-time is 30 min.

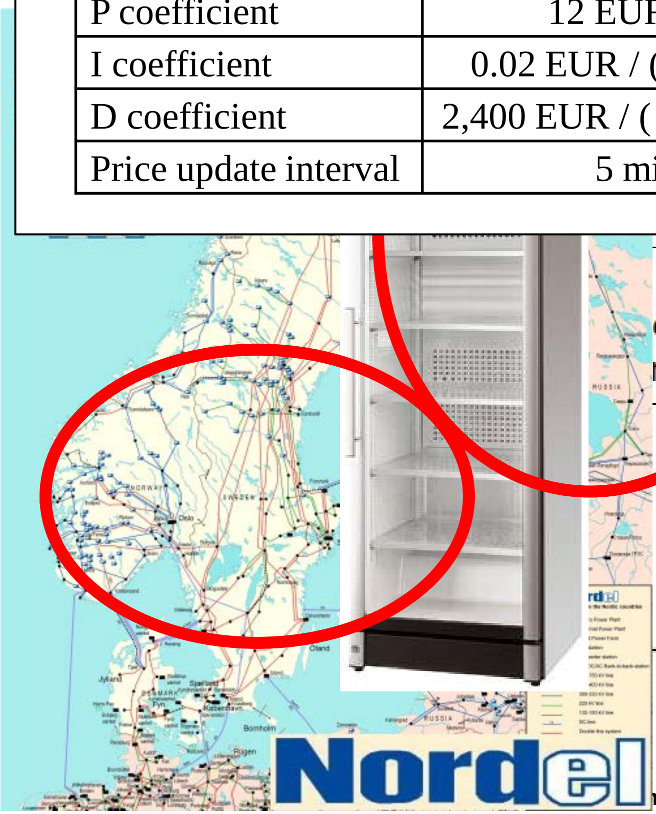
Fig. 6. Aggregate micro-CHP response to 1 EUR/MWh price step. The top figure shows the response to a positive step, and the lower figure the response to a negative step.

Power System Balancing by Distributed Energy Resources and Flexible Demand

TABLE III
PRICE CONTROLLER

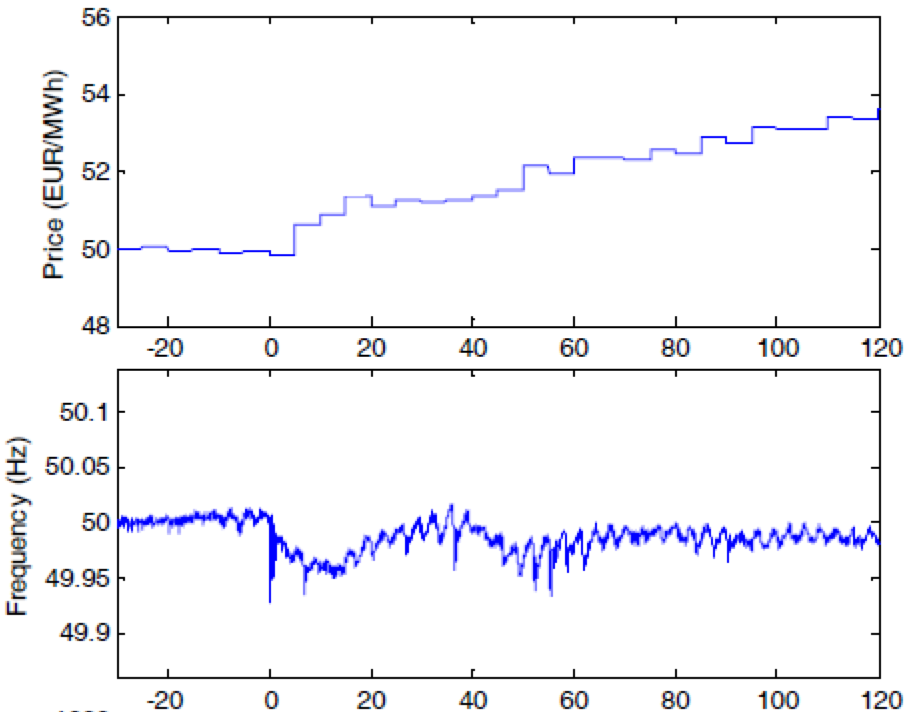
Type	PID
P coefficient	12 EUR / Hz
I coefficient	0.02 EUR / (Hz·s)
D coefficient	2,400 EUR / (Hz/s)
Price update interval	5 minutes

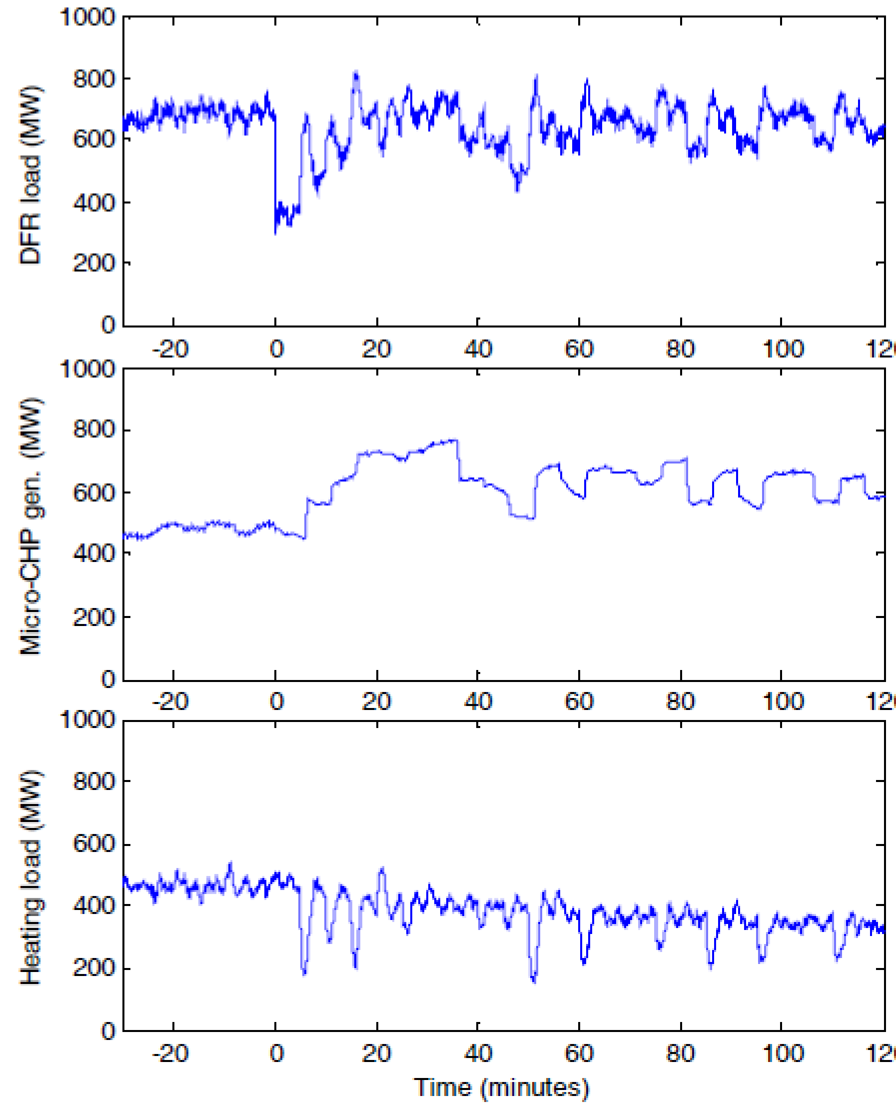




Nominal system frequency	f_0	50 Hz
Rated apparent power	S	70,000 MVA
Inertia constant	H	4 s

Total system response @ 300 MW disturbance (loss of generation)

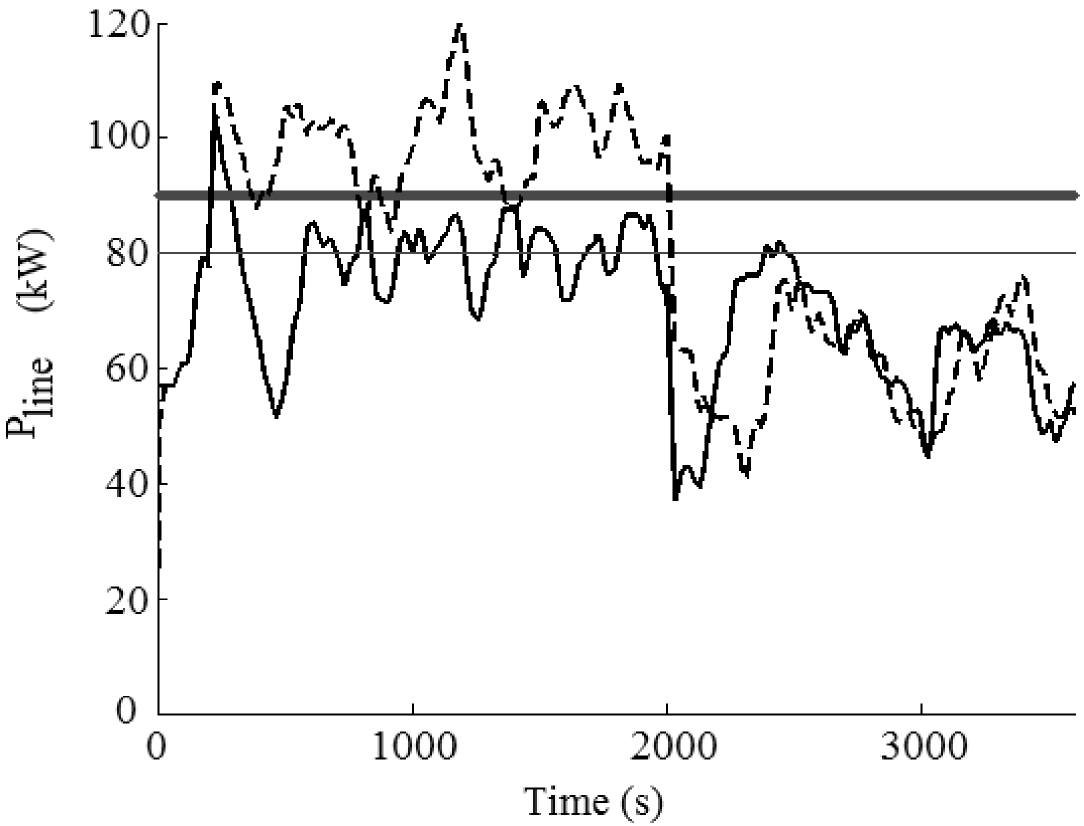


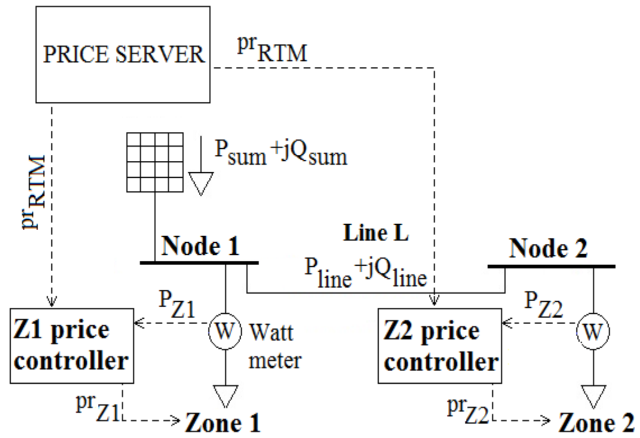


Power System Balancing by Distributed Energy Resources and Flexible Demand

- It is showed that frequency-controlled demand and control-by-price of DER and flexible demand can contribute to system balance in time scale from seconds to hours.
  - Simulations based on verified models
  - Control methods implemented in the laboratory
- Both DFR and control-by-price has tendency to synchronise switching pattern (predominant for the micro-CHP units)
  - Adding randomness in the simulations dissolve this
  - Unlikely to occur in real-life applications
- Frequency is stressed
  - The control-by-price stress the frequency reserves compared to conventional methods
  - Stress the need for the DFR (fast and no tear and wear)
- Control-by-price control algorithm are not optimal (e.g. the synchronised start of micro-CHP units)
  - Optimized for unit profit
  - Need for win-win algorithms

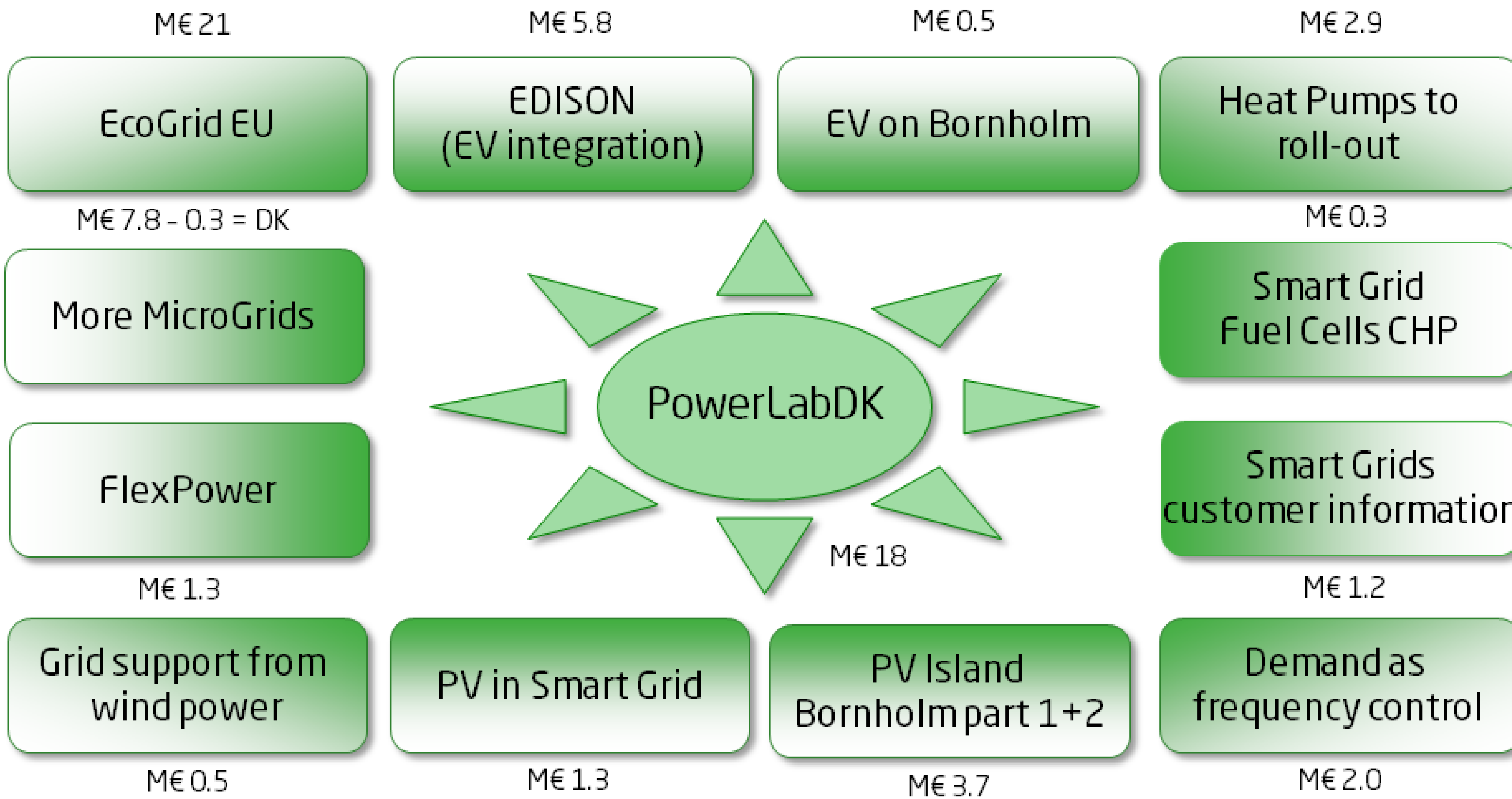
Congestion Management in Distribution Grid by 5 min Dynamic Grid Tariffs





Ref: *IEEE ISGT Europe*, 2011.

Smart Grid related Activities at Bornholm



Some M€ 40 invested in Smart Grid related technologies at Bornholm.

4^{th} IEEE Innovate Smart Grid Technologies Europe 2013

Copenhagen, Denmark
6-9 October 2013

Hosted by Technical University of Denmark

Bringing industry and academia together

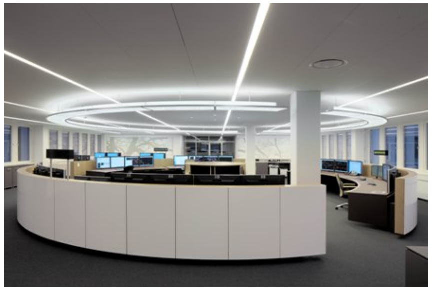
More information:
www.ieee-isgt-2013.eu

IEEE
ISGT 2013
OCTOBER 6-9
COPENHAGEN

DTU

4th IEEE Innovate Smart Grid Technologies Europe 2013

Bornholm power system
(2,000 smart customers and 50% RE)



Smart Grid control room
(wind; state-estimation; VPP's)

EV fleet operation
(e.g. Better Place)

Off-shore wind farms

Den grønne industrikommune
Kalundborg

Smart city Kalundborg

PowerLabDK smart grid labs
(2,000 m^2 lab; field lab at Risø Campus)

IEEE

IEEE PES
Power & Energy Society™

Questions!

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